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Flywheel Calibration of Coherent Doppler Wind Lidar

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Introduction

Within the field of lidar measurement it is often debated why it is necessary to calibrate lidars given that they are 'absolute' instruments. By this is meant that, given two parameters; the laser wavelength and the frequency at which we sample the backscattered light, we are able to calculate the measured radial speed through the well-known equation $V_r = \frac{1}{2}\lambda \cdot \Delta f$. Unlike for example, a cup anemometer or even an LDA, there are no empirical constants that have to be found through a calibration.

Why then do we claim that lidar calibration is necessary anyhow? Probably the most direct answer is that without a calibration (comparison to a reference with known uncertainty) we cannot know that the lidar is getting it right. There could be wrong constants or some (maybe subtle) errors in the algorithm (frequency analysis is not trivial). Only by comparing to a known 'truth' can we be completely sure that the lidar gives the correct speed. More formally, since the uncertainty of the reference is known and, by implication, the reference is traceable to international measurement prototypes, we can assign an uncertainty to the lidar radial speed and claim traceability. In commercial measurements where the outcome can have financial consequences, it will usually be a requirement that the measurements are traceable.

Setup

To perform such a calibration we have constructed a test rig with a stainless steel flywheel, which can be controlled to have a constant rotational speed, and a lidar telescope. As a coherent Doppler lidar is sensitive to the speed component along the beam, the idea is to skim the top surface of the wheel with the beam. If the beam is perfectly tangential to the wheel, the surface speed of the wheel in its entirety will be registered as the radial speed by the lidar. The realisation of this concept is shown in Figure 1 which illustrates the flywheel rig being used to calibrate a lidar. The wheel diameter is 573.46 mm and the distance from the telescope lens to the top of the wheel is 1.54m. In order to measure the rotational speed, a high-precision measuring ring has been fitted to the periphery of the wheel and the tilt angle is measured with an inclinometer mounted on the telescope. The red lines have been inserted manually to illustrate how the (actually invisible) lidar beam is lowered until it just skims the top surface of the wheel.

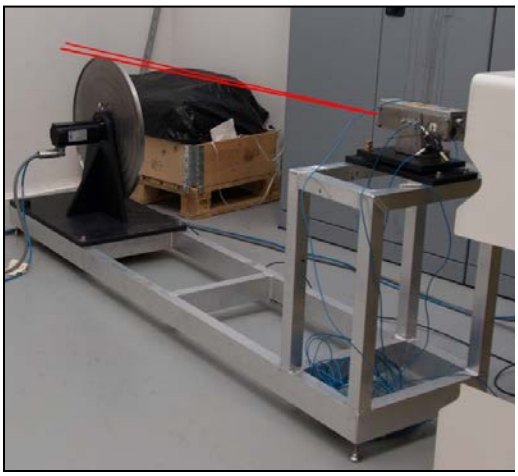

Figure 1. Photo of the flywheel calibration rig with a lidar telescope installed for calibration.

Model

For a truly tangential beam the overlap between wheel and beam would become infinitely small and the backscatter signal from the wheel would disappear. We have therefore developed a simple model for the error in measured speed due to a non-tangential skimming angle. Assuming an infinitely thin beam, we arrive at a very simple and linear expression for the speed ratio angle sensitivity

$$\frac{\partial\left(\frac{V_{lidar}}{V_{wheel}}\right)}{\partial\theta} = -\frac{L}{R},$$

where L is the distance from the telescope to the top of the wheel and R is the wheel radius. For the actual setup, this sensitivity becomes approximately -9.36%/°.

In reality, the laser beam is of course of finite width but as long as the angle θ is steep enough that the entire beam is on the wheel, the approximation is quite good. This is intuitively understood by considering the transverse beam profile, which in our case is close to Gaussian meaning that the centre of the beam will contribute the most to the measured spectrum. Furthermore, two points on either side of the beam centre will see a higher and a lower wheel speed, respectively, and thus to a certain extend cancel each other.

Results

To test the model the flywheel is set to rotate at constant speed and the laser beam gradually lowered while sampling the tilt angle and peripheral speed measured by the measuring ring and lidar, respectively. Figure 2 and Figure 3 show the ratio of the speeds measured by the lidar and the ring as function of tilt angle for two runs with different focus distances and thus beam widths at the wheel. In Figure 2 the focus distance was 3.4 m resulting in a beam diameter of about 10 mm at the wheel. We can easily see that for angles above 0.3° the ratio decreases linearly with angle at a slope of $-9.3\%/°$, very close to the number predicted by the model, and the predicted value for θ=0 is 1.01. However, for angles below 0.3° the curve starts to bend off and this is because the diameter beam now starts to wrap around a significant portion of the periphery of the wheel and the backscatter can no longer be reasonably considered as coming from one point. As a consequence, the radial speed error due to the incorrect angle falls significantly. For the run shown in Figure 3, the focus point is placed as close as possible to the top of the wheel resulting in a very narrow beam of around 0.18 mm. Again, the slope of the fit is seen to agree very well with the model, but we do not see the effect of part of the beam spilling over the top of the wheel because of the narrow beam width. However, here we see a slight oscillation in the measured speed ratio and this is also due to the beam width. The narrow beam only picks up a very limited range of speeds from the surface of the wheel and sometimes these speeds fall in between the frequency bins giving rise to the oscillating behaviour observed in Figure 3.

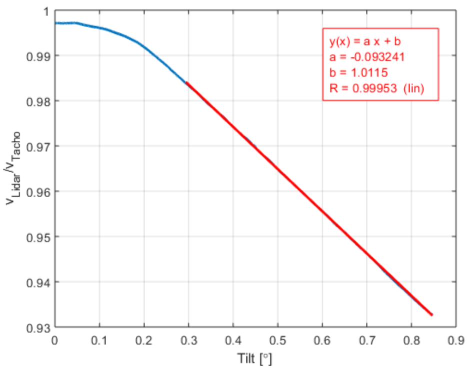

Figure 2 Ratio between the speed measured by the lidar and the measuring ring with a laser beam diameter of about 10 mm. In red is shown a fit to the linear part of the curve.

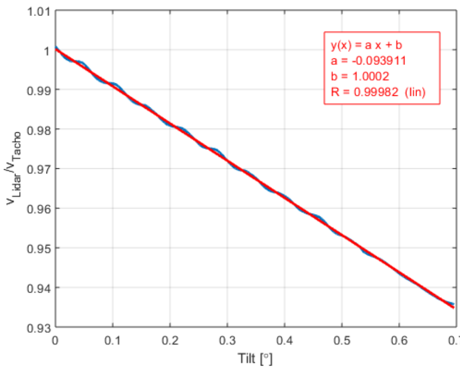

Figure 3 Ratio between the speed measured by the lidar and the measuring ring with a laser beam diameter of about 0.18 mm.

Conclusion

We have constructed a rig for calibration of Doppler wind lidars consisting of a controllable stainless steel flywheel and a mount for the lidar telescope. In theory, it should be possible to measure the tangential speed of the rotating wheel by skimming the top of the wheel with the laser beam. In practice however, this proves difficult as the backscatter signal in that case disappears. We have therefore developed a simple model describing the angular dependency of the error between the true tangential speed and the speed measured by the lidar, and our measurements show a very good agreement with the model as long the entire beam cross-section touches the wheel. With this in mind, we conclude that the proposed method is actually feasible for calibrating coherent Doppler wind lidars.